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RECOMBINATION IN THE E_S - LAYER IN NIGHTTIME

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RECOMBINATION IN THE E_S - LAYER IN NIGHTTIME

(Rekombinatsiya v sloye E_S v nochnoye vremya)

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Abstract

The effective recombination coefficient α is determined by the rate at which the horizontal component H of the geomagnetic field returns to the normal level during bay-like perturbations. It is shown, that as the ionization density N increases, the recombination coefficient α decreases, so that $\alpha = c/N$, where $c = 5 \cdot 10^{-4}$ sec^{-1}. Such α dependence on N is being explained. Finally, solution is given of the ionization balance equation for the particular case of triangular and sinusoidal function of ion formation q.

COVER-TO-COVER TRANSLATION

It was shown in reference [1] , that during bay-like perturbations, increased ionization clouds in the E-region "break-off" the place of corpuscular stream intrusion, and move with the wind. At the same time, the density of their ionization decreases at a rate, determined by that of the recombination. Thus, the investigation of the rate at which the geomagnetic field's component H returns to normal during geomagnetic bays allows a detailed tracing of the recombination process in the E-layer.

Analysis of data obtained in reference [1], has shown that the effective recombination coefficient α is not constant, but varies together with the ionization density.

The object of the present work is a more detailed study and explanation of that dependence, and the obtention of certain formulas expressing the correlation between the rate of ion formation, the ionization density, and the effective recombination coefficient. One must then bear in mind that the recombination coefficient in the E-layer is by one order higher in daytime than in nighttime [2], and the rate of ionization density decrease is basically determined by the rate of decrease in intensity of the ionizing agent, and not by the recombination rate. That is why the results expounded below are only related to recombination in nighttime.

The graph presented in Fig. 1 indicates the course of the recombination coefficient as a function of ionization density N. It was obtained according to data of reference [1]. In spite of a significant dispersion of the points, the dependence of α on N is rather clearly revealed. At the same time, it appears, that $\alpha = c/N$, where c is a a constant factor equal to $6 \cdot 5 \cdot 10^{-4} \text{sec}^{-1}$.

The dependence of the recombination coefficient on the ionization density was studied in further detail by the course of the horizontal component δH of the magnetic field during separate bays according to data of Murmansk geophysical observatory. It was then assumed, that other factors being invariable, the intensity of electric currents in the ionosphere, and consequently of H too, is proportional to ionosphere's conductivity. The latter is in its turn proportional to the density of ionization, i.e. $N = k\delta H$, where k is the factor of proportionality.

If we admit that $\alpha = c/N$, the ionization balance equation takes the form

$$\frac{dN}{dt} = q(t) - cN.$$

If q(t) drops quickly enough, so that after passing the maximum N (or δH) we may estimate that $q(t) = 0$ (the validity of this assumption is discussed below), and the ionization density at the moment t is $N_t = N_{max}\, e^{-ct}$, where N_{max} is the maximum value N and t, and is counted as of the moment of the maximum of N. Taking into account that $N = k\delta H$, we have $\delta H_t = \delta H_{max}\, e^{-ct}$, hence

$$F(t) = \ln \frac{H_{max}}{H_t} = ct, \qquad (1)$$

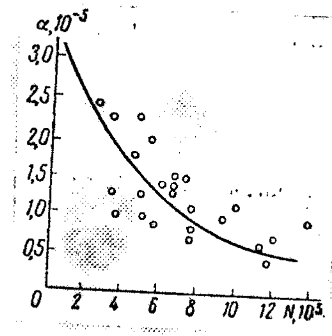


Fig.1

i.e. the maximum of the coefficient c may be found from the rate of H return to normal level. At the same time, essential becomes the circumstance, that the coefficient K, does not enter into the expression (1), and whose magnitude is known to us extremely approximately, i.e. the magnitude c may be determined without making any assumptions concerning the conductivity of the ionosphere [1].

The investigation of concrete bays has shown that the equality (1) is approximately fulfilled in all examined cases.

11 bays were studied in 1960 by such a method. The results obtained are compiled in the following Table:

Time min. / Date Дата	00	06	12	18	24	30	36	42	48	54	60
21.XII 60	0,00	0,18	0,50	0,69	0,96	1,25	—	—	—	—	—
22.XII	0,00	0,26	0,53	0,69	0,83	1,10	1,34	1,41	1,61	1,86	2,20
11.XI	0,00	0,18	0,26	0,33	0,47	0,59	0,79	0,92	0,99	1,16	—
30.VIII	0,00	0,10	0,34	0,53	0,74	0,83	—	—	—	—	—
28.VIII	0,00	0,10	0,26	0,41	0,59	0,69	0,92	1,03	1,28	1,50	1,69
10.VIII	0,00	0,18	0,41	0,59	0,69	0,83	1,03	1,16	1,34	1,48	1,63
17.IX	0,00	0,18	0,26	0,41	0,53	0,64	0,83	—	—	—	—
26.X	0,00	0,10	0,18	0,34	0,53	0,69	0,99	1,31	1,69	1,92	—
21.X	0,00	0,09	0,25	0,46	0,69	0,99	1,29	1,49	1,64	1,82	—
12.XI	0,00	0,09	0,17	0,31	0,38	0,54	0,75	0,83	1,00	1,34	—
mean time	0,00	0,14	0,36	0,47	0,64	0,81	0,99	1,15	1,37	1,51	1,84

An averaged course of F (t) is plotted in Fig. 2. It may be seen from the graph that the obtained values fro F (t) fit well the straight line, i.e. the equality (1) is valid. Consequently, the original assumption that $\alpha = \frac{c}{N}$ is also correct. At the same time $c = 5 \cdot 10^{-4}\ \sec^{-1}$. During average-intensity magnetic storms (δH of the order of 300^{γ} and $N = 6 \cdot 10^{5}\ cm^{-3}$ [1]) the effective recombination coefficient is $\alpha = 1 \cdot 10^{-9}\ cm^{3} \cdot \sec^{-1}$, which agrees well with data of other authors [2].

The difference in values c obtained from the graphs of Fig. 1 and 2 is easy to explain. Indeed, in the first case, c was determined as [illegible] where is the time during which δH diminishes twice [1] while in the second case, it follows from the equality $\delta H_t = \delta H_{max}\, e^{-ct}$ that $c = 1/\tau$, where τ is the time during which δH diminishes e times. Therefore $c_1 = c\frac{\tau}{\tau_1} = \frac{c}{\ln 2} = 1{,}5\, c$, which corresponds to the values obtained.

The obtained dependence of the effective recombination coefficient on ionization density may apparently be explained in the following manner :

The effective recombination is : $\alpha = \alpha_e + \lambda\alpha_i$ [2, 3], where $\alpha_e = 10^{-12}$ cm^2 sec^{-1} is the recombination coefficient of electrons with positive ions, $\alpha_i = 10^{-7} \div 10^{-8}$ cm^3 sec^{-1} is the coefficient of the ionic recombination, and λ is the ratio of concentration of negative ions to that of electrons. The general expression for λ has the form [3]:

$$\lambda = \frac{\beta n - \frac{1}{1+\lambda}\frac{d\lambda}{dt}}{\gamma_1\beta + \gamma_n + N_e(\alpha_i - \alpha_e)}. \tag{2}$$

Simplifying it, we obtain for the E-layer the following magnitudes :

$$\lambda = \frac{\beta_n}{\gamma_1\beta + \gamma_n} \text{ in daytime}$$

and

$$\lambda = \frac{\beta}{\gamma} \text{ in nighttime.}$$

Here $\gamma_1 = 10^{14}$ is the coefficient of electron "photo-unsticking" $\gamma_n = 10^{-15}$ to 10^{-16} is the coefficient of electron "unsticking" as a result of collisions ; $\beta = 10^{-15}$ to 10^{-16} is the adhesion (sticking) coefficient of electrons and n is the concentration of neutral molecules.

As may be seen from these expressions, the term $N_e\ (a_i - a_e)$ in the denominator of formula (2) is usually neglected in view of its smalness in comparison with the remaining terms. However, it may grow in nighttime during magnetic storms becoming greater than the remaining terms.

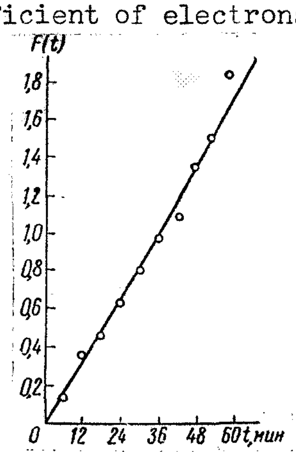
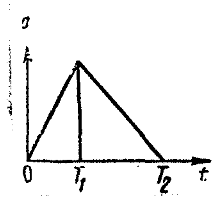
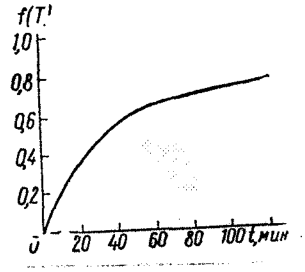


Fig. 2





Indeed, $\gamma_1\beta$ disappears. $\gamma_n = 10^{-3}$ to 10^{-4}, while $N_e \alpha_i$ during average magnetic storms (at $N_e \geqslant 10^5$), is $1 \cdot 10^5 (10^{-7} \div 10^{-8}) = 10^{-2} \div 10^{-3}$. In that case $\lambda = \beta_n/(\alpha_i N_e)$, which corresponds to the magnitude λ, obtained by Ghosh [4] for the F-region in nighttime. Then

$$\alpha = \lambda \alpha_i = \frac{\beta_n}{N_e} = \frac{c}{N_e},$$

which agrees with the obtained experimental results. At the same time, it is obvious that

$$\beta = \frac{c}{n} = \frac{5 \cdot 10^{-4}}{10^{12}} = 5 \cdot 10^{-16},$$

which agrees well with the magnitude β, brought out by other authors [2, 3].

Let us now derive certain correlations linking between themselves the rate of formation of ions q (t), the coefficient c and the ionization density N (t).

On the basis of the above-expounded data, the ionization balance equation for the E-layer in nighttime has the form $dN/dt = q(t) - cN$. Let us resolve this equation for the particular case when q (t) has the form of a triangular pulse (Fig. 3), i.e.

$$\begin{aligned} q(t) &= k_1 t && \text{at} \quad 0 \leqslant t \leqslant T_1; \\ q(t) &= k_1 T_1 - k_2 (t - T_1) && \text{at} \quad T_1 \leqslant t \leqslant T_2; \\ q(t) &= 0 && \text{at} \quad t \geqslant T_2, \end{aligned}$$

Assuming that $N_{t=0}=0$, we have,

$$\left.\begin{aligned}
&N(t)=\frac{k_1 t}{c}+\frac{k_1}{c^2}e^{-ct}-\frac{k_1}{c^2}, && 0\leqslant t\leqslant T_1\\
&N(t)=\left(\frac{k_1}{c^2}e^{-cT_1}-\frac{k_1+k_2}{c^2}\right)e^{-c(t-T_1)}-\frac{k_2}{c}(t-T_1)+\frac{k_1T_1}{c}+\frac{k_2}{c^2}, && T_1\leqslant t\leqslant T_2\\
&N(t)=\left[\left(\frac{k_1}{c^2}e^{-cT_1}-\frac{k_1+k_2}{c^2}\right)e^{-c(T_2-T_1)}-\frac{k_2}{c}(T_2-T_1)+\frac{k_1T_1}{c}+\frac{k_2}{c^2}\right]e^{-c(t-T_2)}, && t\geqslant T_2
\end{aligned}\right\}\quad(3)$$

From the equality (3) it is easy to find the time lag τ of the maximum of ionization density N relatively to the maximum of q. Indeed, it follows from the condition dN/dt :

$$\tau=\frac{1}{c}\ln\frac{k_1+k_2-k_1e^{-cT_1}}{k_2}$$

whence

$$N_{max}=\frac{k_1T_1}{c}-\frac{k_2}{c^2}\ln\frac{k_1+k_2-k_1e^{-cT_1}}{k_2},$$

where N_{max} is the ionization density maximum.

It may be seen from these formulas, that the relative course of the ionization density and the time lag τ depend only on the form of the pulse q, and do not depend on its absolute magnitude.

Let us examine in more detail the obtained correlations for the simplest case of a symmetric pulse $q(t)$, i.e. when $k_1=k_2=k$; $T_1=T_2=T$, and $kT=q_{max}$. In that case *)

$$\tau=\frac{1}{c}\ln\left(2-e^{-cT}\right);\qquad(4)$$

$$N_{\text{макс}}=\frac{q_{\text{макс}}}{c}\left[1-\frac{2}{cT}\ln\left(2-e^{-cT}\right)\right]=\frac{q_{\text{макс}}}{c}f(T),\qquad(5)$$

*) N_{makc} stands for N_{max}

where q_{max}/c represents the ionization density, reached at the infinite duration of the pulse q (t).

The course of f (T) is shown in Fig.4. It may be seen from the graph, that for usual durations of the pulse (T = 10 $\div$ 30 min.) in case of bay-like disturbances, f (T) = 0.2 $\div$ 0.5. Thus, for an increase in ionization density till 5 10^5 cm^{-3}, corresponding to an average geomagnetic bay intensity ($\delta H = 250^{\gamma}$), the rate of ion formation must increase to 500 – 1000 cm^3 sec^{-1}. N_m drops sharply at pulse q duration increase, and at T = 20 sec, the pulse q , of same amplitude as in the first case, will increase the ionization density only to $5 \cdot 10^3$ cm^{-3}. Therefore, short-term pulsations, even of great intensity, do not cause notable ionization density variations, and consequently of geomagnetic effects either.

In determining the effective recombination coefficient by means of time lag of ionization density maximum relatively to the maximum rate of ion formation, formula $\tau = \frac{1}{2} \alpha N$ is generally used [5, 6]. This formula is obtained in the assumption that α = const. Analysis of formula (4) shows, that for average pulse q (t) durations (T = 10 $\div$ 30 min),

$$\tau = (0.4 \div 0.7) \frac{1}{c} = (0/4 \div 0.7) \frac{1}{\alpha N}$$

i.e. the usually utilized formula for τ remains valid also in the case $\alpha = c/N$.

Let us now examine the case, when q(t) has no longer the form of a solitary pulse, but that of a periodical function. Let be

$$q(t) = q_0 + A \sin \omega t,$$

where q_0 is the average level near which oscillations of q take place, A is the amplitude of variations of q and $\omega = 2\pi/T_0$ (here T_0 is the period of q oscillations).

In that case the solution of the ionization balance equation has the form

$$N = \frac{q_0}{c}(1 - e^{-ct}) + \frac{A\omega}{c^2+\omega^2}\left[e^{-ct} + \frac{\sqrt{c^2+\omega^2}}{\omega}\sin(\omega t - \varphi)\right],$$

where $\varphi = \operatorname{arc\,tg} \omega/c$.

In case of fast oscillations (T_0 of the order of several minutes and less)

$$\omega^2 \gg c^2$$

$$N = \frac{q_0}{c}\left((1 - e^{-ct}\right) + \frac{A}{\omega}e^{-ct} + \frac{A}{\omega}\sin(\omega t - \varphi),$$

i.e. at fast oscillations q the ionization density grows exponentially, approaching the boundary value q_0/c, while undergoing oscillations with an amplitude A/ω, much lower than the maximum level q_0/c.

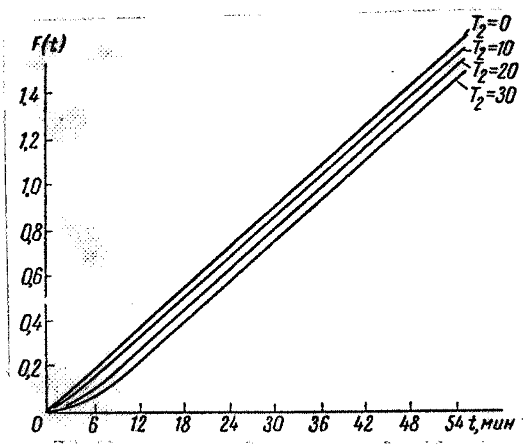


Fig. 5.

Let us now examine the effect on the precision of magnitude c determination of the fact that q(t) breaks suddenly after the maximum. Let us compute for that purpose F(t) for a series of traingular pulses q with $T_1 = 30$ min. and $T_2 = 30$, 20, 10 and 5 min. The corresponding course of F(t) is shown in Fig. 5. It may be seen from the graphs that the form of F(t) varies with T_2 only during the first several minutes, after which the graph F(t) rapidly tends to a stright line, parallel to F (t) = ct. For a duration of the rear front of the pulse (tq) of less than 10 min., the graph F(t) does not practically differ from the limit straight line. Therefore, even if q(t) diminishes slowly, c may be determined with a sufficient precision according to the rectilinear portion of the diagram F (t). It must be noted, however, that the initially-slowed down course of the curve could not be detected for all the 11 examined bays. This implies that the ionizing flux breaks rather rapidly.

**** E N D ****

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